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Da Ros, Francesco; Lillieholm, Mads; Yankov, Metodi Plamenov; Guan, Pengyu; Hu, Hao; Forchhammer, Søren; Galili, Michael; Oxenløwe, Leif Katsuo

Published in:
Proceedings of ECOC 2017

Publication date:
2017

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Da Ros, F., Lillieholm, M., Yankov, M. P., Guan, P., Hu, H., Forchhammer, S., Galili, M., & Oxenløwe, L. K. (2017). Impact of Signal-Conjugate Wavelength Shift on Optical Phase Conjugation-based Transmission of QAM Signals. In *Proceedings of ECOC 2017* IEEE.

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Impact of Signal-Conjugate Wavelength Shift on Optical Phase Conjugation-based Transmission of QAM Signals

F. Da Ros, M. Lillieholm, M.P. Yankov, P. Guan, H. Hu, S. Forchhammer, M. Galili and L.K. Oxenløwe

⁽¹⁾ Department of Photonics Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark fdro@fotonik.dtu.dk

Abstract The impact of signal-conjugate wavelength shift on nonlinearity compensation through optical phase conjugation is investigated for 64- and 256-QAM. Wavelength-shift independent achievable rate improvements between 0.2 and 0.3 bit/symbol are reported for shifts up to 30 nm in 500-km transmission.

Introduction

Current optical transmission systems are limited in their transmission reach and rate by the Kerr nonlinearity in optical fibers, which sets an upper limit on the power that can be transmitted without significantly distorting the data signal. Several techniques are being investigated to provide compensation for the nonlinear distortion, both in the digital domain, e.g. digital backpropagation (DBP), and all-optically, e.g. through optical phase conjugation (OPC) ¹⁻⁶. Compared to DBP, OPC enables better nonlinearity compensation for wavelength division multiplexing (WDM) systems without increasing the electrical bandwidth of the transceivers². Ideal nonlinearity compensation through OPC requires symmetric power and dispersion profiles of the link with respect to the position of the OPC stage, as well as a link with no wavelength dependent dispersion and no polarization mode dispersion (PMD). The impact of link symmetry has been extensively investigated³, and the effects of PMD have been numerically analysed⁴. However, to the best of our knowledge no systematic investigation of the impact of wavelength dependent dispersion on OPC systems has been reported. Understanding the impact such wavelength dependency is critical, as the OPC is typically implemented using four-wave mixing (FWM), resulting in a wavelength shift between the signal and its conjugated copy. Even though schemes providing wavelength-shift free operation are being investigated⁶⁻⁸, the

techniques reported so far are limited to single-channel operation and would yield a mirroring of a WDM channel band⁶.

In this work, we investigate the impact of signal-conjugate wavelength shift on the improvement provided by the OPC operation. We consider different shifts in a transmission system using 64- and 256-quadrature amplitude modulation (QAM) signals.

Experimental setup

The experimental setup is shown in Fig. 1. A 64- or 256-QAM signal is generated from an external cavity laser (ECL, 10-kHz linewidth) modulated in an IQ modulator driven by an arbitrary waveform generator (AWG, 64 GSa/s) operating at 10 GBd and 16 GBd. The QAM symbols are interleaved with quadrature phase shift keying (QPSK) pilots at a rate of 10%, and pulse shaped with square root raised cosine (roll-off factor=0.1). The transmitter rate has been set to 4.5 bit/QAM symbol, and a split-and-combine polarization emulator (Pol. mux) generates a polarization division multiplexed (PDM) signal, resulting in rates of 81 Gb/s and 130 Gb/s. The PDM signal is polarization scrambled and launched into the first transmission link. Each of the two links consists of three 84-km spans of standard single mode fiber (SSMF), with erbium doped fiber amplifiers (EDFAs) compensating for the fiber loss. While such a link configuration is not optimum for nonlinearity compensation by OPC, due to the lack of symmetry, it does represent a configuration used in many deployed links. OPC

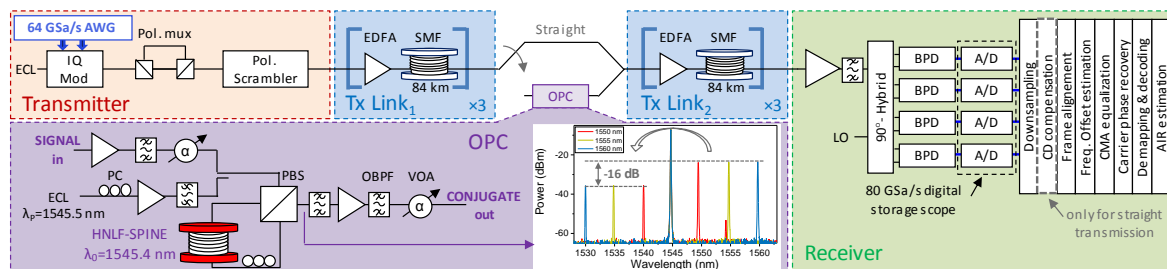


Fig. 1: Experimental setup for the comparison of *straight* and the *OPC-based* transmission. Inset shows the optical spectra at the output of the PBS, highlighting the three wavelength shifts considered: 10 nm, 20 nm, 30 nm.

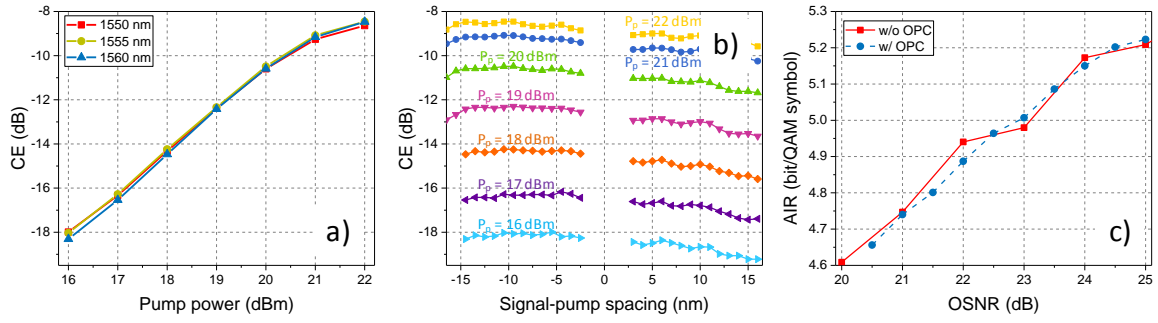


Fig. 2: a) Conversion efficiency (CE) as a function of the pump power (in straight HNL configuration) for the three signal wavelengths considered; b) CE as a function of the signal-pump spacing for different pump power levels, yielding the conversion bandwidth; c) Achievable information rate (AIR) as a function of the signal OSNR in back-to-back configuration without and with polarization-independent OPC for 16-GBd 256-QAM.

has already been reported to provide improvements also for such asymmetric links⁵. After transmission, the signal is received in an 80-GSa/s pre-amplified coherent receiver (33-GHz analog bandwidth) with a 10-kHz linewidth ECL as local oscillator (LO). Offline digital signal processing (DSP) is then performed consisting of low-pass filtering, chromatic dispersion (CD) compensation (in straight configuration only), frequency offset estimation, pilot-based time domain equalization, and carrier phase recovery as in [9]. The metric chosen to evaluate the performance is the achievable information rate (AIR), estimated by using the auxiliary probability distribution derived from the phase recovery algorithm as discussed in [9]. The AIR is calculated over more than 10^6 symbols to guarantee a reliable estimation and it is used to compare *straight transmission*, where the two links of 3 fiber spans are connected directly, with the *OPC-based transmission*, where the OPC operation is performed between the two links. In order to evaluate the dependence of the improvement provided by OPC on the wavelength shift, the signal wavelength has been varied by placing the signal at 1550 nm, 1555 nm and 1560 nm, corresponding to signal-conjugate wavelength shifts of 10 nm, 20 nm and 30 nm, respectively (pump wavelength of 1545.5 nm).

OPC stage characterization

The OPC stage is based on single-pump FWM using a 500-m highly nonlinear fiber (HNL-SPINE) as the nonlinear medium. The FWM performance is shown in Fig. 2 (a)-(b) under continuous wave (CW) operation with the pump placed at 1545.5 nm. The conversion efficiency (CE) scales quadratically with the pump power (P_p) up to $P_p = 21$ dBm (Brillouin scattering threshold). Identical CE levels are achievable for the three signal wavelengths considered (Fig. 2(a)) leading to equivalent optical signal to noise ratio (OSNR) for the three conjugated copies. The full conversion bandwidth is shown in Fig. 2(b) achieving an operational bandwidth for the OPC stage covering most of

the C-band with less than 2 dB of CE variation. To provide polarization-independent OPC operation, a polarization-diversity loop² is used (see Fig. 1, lower left) with a polarization-dependence below 0.4 dB. The pump power per propagation direction is 17 dBm resulting in a CE of -16 dB. The spectra at the output of the diversity loop are shown in the inset of Fig. 1. The input signal power into the OPC has been optimized (in terms of AIR) to -2 dBm, and kept constant by using a variable optical attenuator (VOA). At the output of the polarization beam splitter (PBS), two OBPFs with an EDFA in between and a VOA are used to suppress signal and pump and to amplify the conjugated copy such that the input power to the first EDFA of Link 2 is the same as in straight transmission. Low-penalty operation of the OPC stage is verified by back-to-back measurements with and without OPC performing OSNR loading at the receiver input. The estimated AIRs as functions of the signal OSNR are shown in Fig. 2(c) for 16-GBd 256-QAM, confirming that no signal degradation is introduced by the OPC stage.

Nonlinearity compensation results

In order to evaluate the improvement provided by nonlinearity compensation through OPC, the launched power into each span has been varied and the AIR has been measured at the receiver for the three signal wavelengths. The comparison between straight and OPC-based transmission is shown in Fig. 3(a) and (b) for 10-GBd 64-QAM and 10-GBd 256-QAM, respectively. In the linear transmission regime, straight and OPC-based transmissions show similar performance. The CE is sufficient to ensure that the OSNR of the conjugate signal is determined by the OSNR of the original signal confirming that the OPC does not degrade the signal. In the nonlinear regime, the nonlinearity compensation provided by OPC is clearly seen for both modulation formats. OPC enables an increase in the optimum launched power, from 0 dBm to +3 dBm, as well as a higher received AIR. More importantly, the three signal

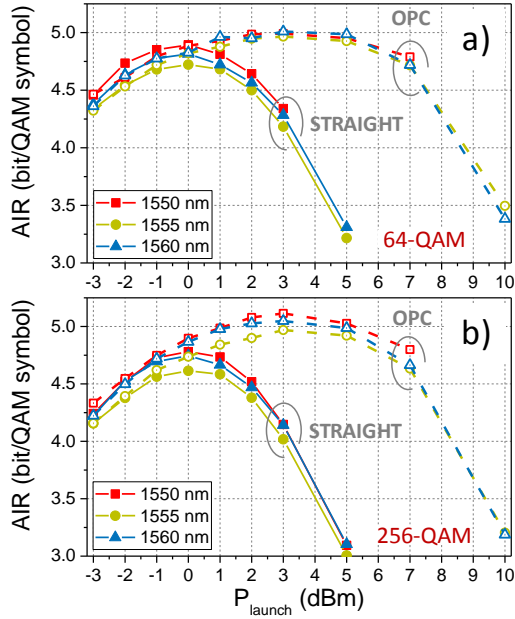


Fig. 3: Estimated AIR as a function of the launched power for *straight* and *OPC-based* transmission: 10-GBd 64-QAM (a) and 256-QAM (b) and the three signal wavelengths under investigation.

wavelengths show nearly identical improvements. The slightly lower AIR for the 1555-nm signal (both with and without OPC) is due to a minor wavelength dependence of the transmitter setup already noticeable in the linear regime. The difference in wavelength shift between the three configurations corresponds to an accumulated dispersion mismatch of approx. 215 ps/nm, 430 ps/nm and 646 ps/nm compared to a wavelength-shift free OPC. Note that a 30-nm wavelength shift is close to the maximum shift produced by an OPC stage covering the full C-band. The overall AIR improvement, defined as the difference in AIR between straight and OPC-based transmission at the optimum launched power, for the three signal wavelengths and all four pairs of modulation format and baudrate under investigation, are reported in Fig. 4. For all these cases, no notable wavelength dependent improvement variations are shown. The minor differences between signal wavelengths fall within the precision of the measurement of

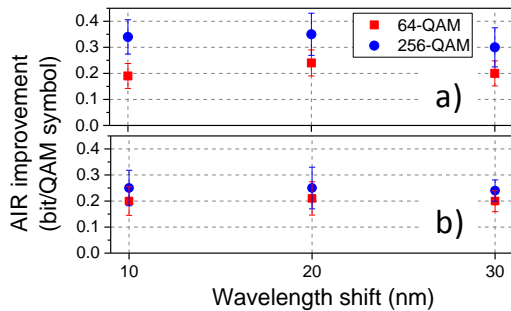


Fig. 4: AIR improvement as a function of the wavelength shift for (a) 10 GBd and (b) 16 GBd signals.

approx. ± 0.05 bit/QAM symbol (see error bars in Fig. 4).

Conclusions

We have investigated the impact of wavelength shift between a signal and its conjugated copy on the improvement provided by OPC in a 500-km dispersion-uncompensated link with lumped EDFA amplification. Three signal wavelengths, 1550 nm, 1555 nm and 1560 nm, are considered, corresponding to a signal-conjugate wavelength shift of 10 nm, 20 nm and 30 nm, respectively. AIR improvements between 0.2- and 0.3 bit/QAM symbol provided by OPC are reported for 64-QAM and 256-QAM at 10 GBd and 16 GBd, with no impact of the wavelength shift on the improvement. We believe that this constitutes an important confirmation of the great potential of OPC for nonlinearity compensation in practical communication links.

Acknowledgements

This work is supported by CoE SPOC, ref. DNR123 and DFF-4005-00558 project NANO-SPECs.

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